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THE CONTINUUM PART OF (^3He , t) SPECTRA AT $E_{^3\text{He}} = 52 \text{ MeV}$

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Inclusive (^3He , t) spectra for various targets are presented. For ^{28}Si , (^3He , pt) coincidence data allow a quantitative unraveling into three components, due to a breakup-transfer mechanism, direct charge exchange and an evaporation process (^3He , dd) and (^3He , $p^3\text{He}$) coincidence data support the breakup-transfer mechanism.

Inclusive triton spectra from ^3He -induced reactions over a broad energy range have been found in investigations aimed to search for magnetic resonances [1,2] to exhibit a broad bell-shaped structure. It has been suggested by Nomura [3] that this continuum arises from a combined breakup-transfer reaction in which the ^3He projectile breaks up into a proton and a deuteron followed by neutron pickup from the target by the deuteron. In a systematic study on different targets, Bousshid et al. [4] recently showed that the bell shape is a common characteristic of triton spectra in ^3He -induced reactions. In addition to the (^3He , pd) (pd, pt) reaction they point to other possible mechanisms that might contribute to the observed cross sections: the (^3He , t) charge-exchange reaction, the (^3He , α^*)(α^* , tp) reaction and other multistep processes.

In this work we present, along with inclusive spectra on various targets, a complete set of data on ^{nat}Si consisting of inclusive triton spectra and (^3He , pt) coincidence measurements. From these data it is possible to determine the nature and the relative importance of the different reaction mechanisms. As will be shown, these mechanisms are: (1) the (^3He , t) charge-exchange reaction, (2) a breakup-transfer process giving a bell shaped continuum and (3) an evaporation-like process.

The data have been obtained with $\Delta E - E$ -veto telescopes consisting of solid-state counters with thicknesses of 0.1, 5 and 2 mm, respectively. The 52 MeV momentum analyzed ^3He beam was obtained from the

KVI cyclotron. Targets were selfsupporting with thicknesses of 1.0–2.5 mg/cm². Data have been recorded event by event for off-line analysis.

In fig. 1 inclusive triton spectra are shown for the

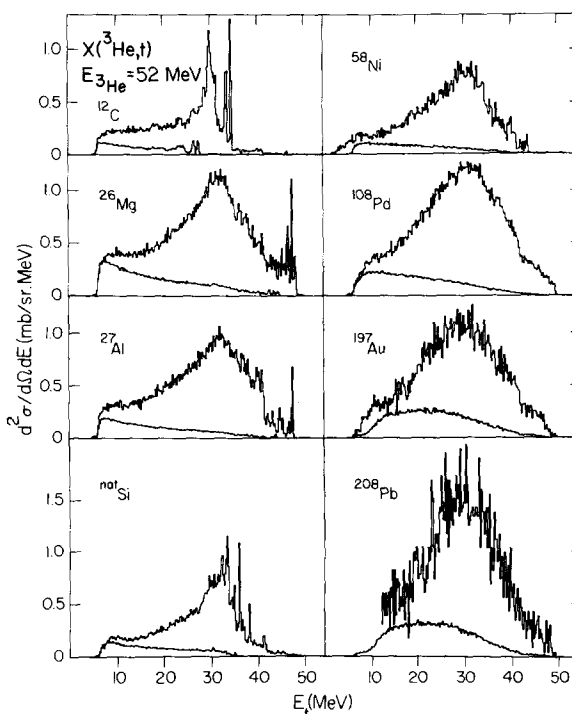


Fig. 1. Singles triton spectra from 52 MeV ^3He induced reactions at $\theta_t = 10^\circ$ on ^{12}C , ^{26}Mg , ^{27}Al , ^{nat}Si , ^{58}Ni and ^{208}Pb and at $\theta_t = 15^\circ$ on ^{108}Pd and ^{197}Au . For each target also the spectrum at $\theta_t = 50^\circ$ is presented (lower curve).

targets ^{12}C , ^{26}Mg , ^{27}Al , natSi , ^{58}Ni , ^{108}Pd , ^{197}Au and ^{208}Pb at a forward angle (10° or 15°) and at a more backward angle (50°). Similar to the observation of ref. [4] we find a bell-shaped continuum for all targets at forward angles. The spectra for ^{12}C and natSi show a significantly lower cross section in the continuum part. As will be shown later on, this is due to their very negative Q values for the $(^3\text{He}, \text{tp})$ process and thus their smaller phase space. At the same time these spectra exhibit a pronounced level structure that is due to the $(^3\text{He}, \text{t})$ charge-exchange reaction. A new feature of all spectra is the evaporation-like component that becomes clearly visible at 50° . In the forward-angle spectra it explains the asymmetry of the spectra which was also observed in ref. [4].

Kinematically complete coincidence experiments are necessary to identify the reaction mechanism responsible for a continuum spectrum. Such an experiment has been carried out for a natSi target (92.2%

^{28}Si). ^{28}Si is a particularly suitable target, since the $(^3\text{He}, \text{t})$ reaction leads to ^{28}P , which is proton unstable above $E_x = 2.06$ MeV with no other competing decay channels below $E_x = 9.53$ MeV. Therefore the pro-

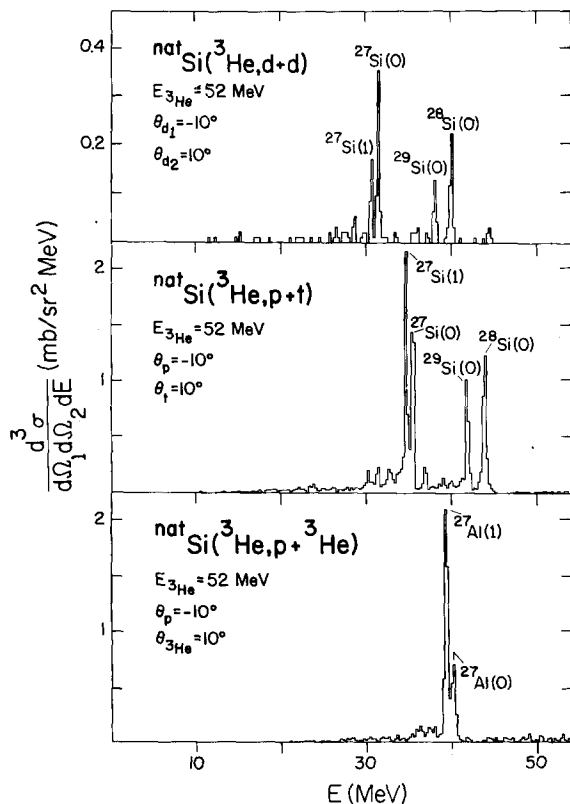


Fig. 2. Total-energy spectra for the $(^3\text{He}, \text{dd})$, $(^3\text{He}, \text{pt})$ and $(^3\text{He}, \text{p}^3\text{He})$ reactions on natSi at $\theta_1 = -10^\circ$ and $\theta_2 = 10^\circ$.

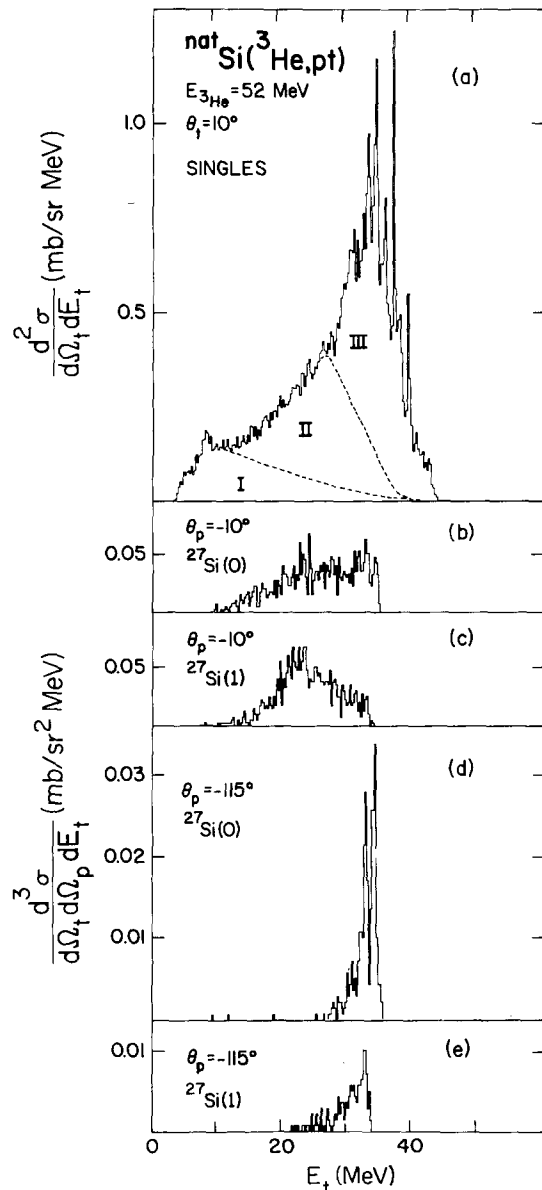


Fig. 3. Comparison between (a) the singles spectrum at $\theta_t = 10^\circ$ and tritons in coincidence with protons at (b) $\theta_p = -10^\circ$ gated on ^{27}Si (g.s.), (c) $\theta_p = -10^\circ$ gated on ^{27}Si (0.78 MeV). (d) $\theta_p = -115^\circ$ gated on ^{27}Si (g.s.), (e) $\theta_p = -115^\circ$ gated on ^{27}Si (0.78 MeV).

nounced structures observed in the inclusive spectrum can also be studied through their proton decay.

With one telescope fixed at 10° an angular correlation was taken in which the other telescope covered the angular range $-155^\circ < \theta < 155^\circ$ in 25 steps.

In fig. 2 total kinetic energy (TKE) spectra are shown for proton–triton, deuteron–deuteron and proton– ^3He coincident events. Since the recoil energies of the daughter nucleus are very small the reaction Q value is given by the TKE-loss and one identifies the states excited in these reactions. The spectra are very similar to spectra from single-nucleon pickup; the ground state and first excited state in ^{27}Si (^{27}Al) are the only ones that are populated with an appreciable cross section [5]. Since ^{28}Si is a self-conjugate nucleus, a direct comparison between the neutron-pickup reactions (^3He , pt) and (^3He , dd) and the proton-pickup reaction (^3He , $p^3\text{He}$) is possible. In addition the neutron pickup from the naturally present isotopes ^{29}Si and ^{30}Si is observed to be strong. Gating on either the ground state or the first excited state in ^{27}Si , triton spectra are projected out. These are shown in fig. 3 for tritons detected at 10° , along with the inclusive triton spectrum.

The shape of the evaporation-like component (I) is given by the shape of the inclusive spectra at $\theta_t > 50^\circ$. This component does not show up in any of the coincidence spectra, figs. 3b–3e. For protons detected in the forward direction the coincidence spectra are dominated by a bell-shaped component (Figs. 3b and 3c). These spectra determine the shape of component II in the singles triton spectra (fig. 3a). The centroid energy of this component is approximately given by $E_t = \frac{2}{3}E_{^3\text{He}} + Q(^3\text{He}, \text{pt})$. Area III corresponds to the direct charge-exchange component which dominates at backward proton angles (figs. 3d and 3e), where component II is negligible. The coincidence yields for the (^3He , pt) reactions leading to the $^{27}\text{Si}(\text{g.s.})$, ^{27}Si (first exc.), $^{28}\text{Si}(\text{g.s.})$ and $^{29}\text{Si}(\text{g.s.})$ states have been integrated over the proton angles under the assumption of a linear dependence on the azimuthal angle [6]. This results in a total yield of 6.7 ± 0.7 mb/sr for the components II and III together compared to 8 ± 1 mb/sr in the singles spectrum. Thus it has been shown that the inclusive triton spectrum can be quantitatively explained by the contributions from three different processes.

The one-nucleon pickup character of the total-ener-

gy spectra leaves as the most likely candidates for the reaction mechanism: (1) the breakup-transfer mechanism proposed by Nomura [3] which may be extended to incorporate the processes (^3He , pd)(pd, pt), (^3He , pd)(pd, $p^3\text{He}$) and (^3He , dp)(dp, dd) and (2) one-nucleon pickup by the ^3He projectile: (^3He , $^4\text{He}^*$) and (^3He , $^4\text{Li}^*$) followed by decay of the unstable ejectiles.

In fig. 4 projected spectra are shown from the (^3He , pt), (^3He , dd) and (^3He , $p^3\text{He}$) reactions taken at $\theta_1 = 10^\circ$ and $\theta_2 = -10^\circ$. In all these spectra a relative energy scale for the two outgoing light particles is given, along which the positions of known [7] resonances in ^4He and ^4Li are indicated. The ($p + ^3\text{He}$) spectra are clearly inconsistent with decay of $^4\text{Li}^*$. For the (d+d) system the only state through which the reaction might proceed is the $J^\pi = 0^+$, $T = 0$ state in ^4He at $E_x = 25.5$ MeV with $\Gamma = 2.9$ MeV. A deuteron spectrum calculated for these parameters is in striking disagreement with the experimental spectrum (solid curve in fig. 4).

Although the (p+t) data are at first sight not inconsistent with decay of $^4\text{He}^*$, such a process implies that the projected triton spectrum would shift with a change in the angle β between the two detectors, since the relative-energy scale changes. In contrast, the projected spectra for all three processes are found to remain unchanged upon changing β . This observation, combined with the analogy between the processes (^3He , pt), (^3He , dd) and (^3He , $p^3\text{He}$), seems sufficient evidence to discard the decay through $^4\text{He}^*$ or $^4\text{Li}^*$ as an important mechanism.

A mechanism that is consistent with the observation that the projected spectra are nearly independent of β , is the breakup-transfer process. In fact in (^3He , pt) and (^3He , $p^3\text{He}$) it implies a quasi-free (d, t) or (d, ^3He) reaction, respectively, in which the proton is a spectator. Likewise (^3He , dd) should be viewed as a quasi-free (p, d) reaction where the second (fast) deuteron is a spectator.

In PWIA the energy spectra are proportional [6,8,9] to the relative momentum distribution $\Phi^2(p)$ of the proton and deuteron within the ^3He projectiles:

$$d^3\sigma/dE \, d\Omega_1 \, d\Omega_2 \quad (1)$$

$$= |T_{2A}|^2 \times [\Phi(|\mathbf{p}_1 - \frac{1}{3}m_1\mathbf{p}_{^3\text{He}}|)]^2 \times \text{phase space},$$

where particle 1 is the spectator. T_{2A} is the T -matrix that describes the reaction of particle 2 with the tar-

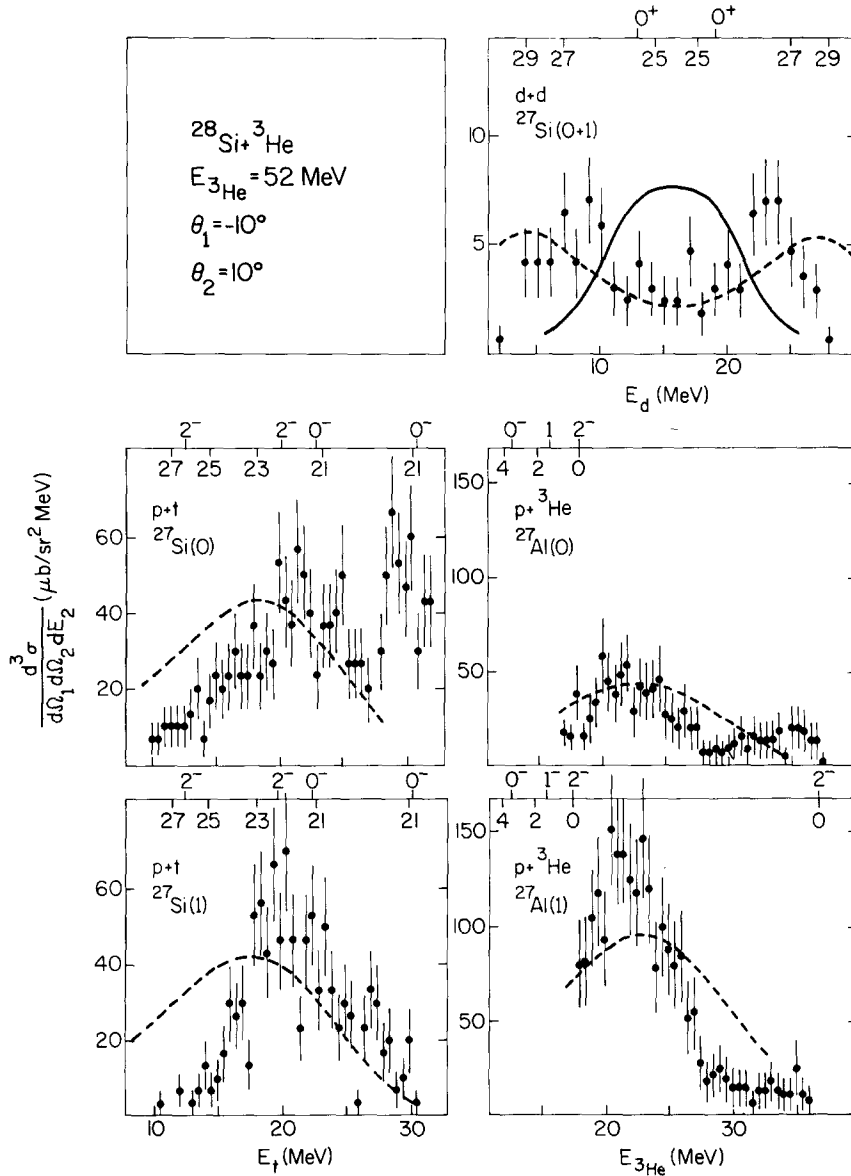


Fig. 4. Coincidence spectra gated on the ground state and/or first excited state in the final nucleus for the (^3He , dd), (^3He , pt) and (^3He , $p^3\text{He}$) reactions on ^{28}Si at $\theta_1 = -10^\circ$ and $\theta_2 = 10^\circ$. The dashed curves indicate the PWIA predictions (see text), normalized to the data. Excitation energies relative to the ground state in ^4He and ^4Li are indicated above each spectrum together with known resonances. The solid line in the (^3He , dd) spectrum corresponds to $^4\text{He}^*$ decay (see text). The structures observed in the high-energy part of the triton spectrum [$^{27}\text{Si}(\text{g.s.})$] arise from proton decay of states in ^{28}P (see also fig. 3d).

get. In fig. 4 curves corresponding to this expression are shown for a Hulthén-type ^3He wave-function with parameters $\alpha = 0.419$ and $\beta = 1.36$ [10], where $|T_{2A}|^2$ has been taken to be a constant. Its values for the dif-

ferent curves are: 720 ($p + t$, $^{27}\text{Si}(\text{g.s.})$), 680 ($p + t$, ^{27}Si (first exc.)), 650 ($p + ^3\text{He}$, $^{27}\text{Al}(\text{g.s.})$), 1340 ($p + ^3\text{He}$, ^{27}Al (first exc.)) and 300 ($d + d$, $^{27}\text{Si}(\text{g.s.} + \text{first exc.})$) in the units MeV^2fm^6 .

The relative intensities of the ground states and first excited states in (^3He , pt) and (^3He , p ^3He) are found to be similar to the DWBA predictions for cross sections of the free (d, t) and (d, ^3He) reactions at $E_d = 34$ MeV (same incident velocity as ^3He of 52 MeV). This again is consistent with eq. (1).

In conclusion we have shown that the singles triton spectra from ^3He -induced reactions are composed of three major contributions: (i) (^3He , t) charge exchange, (ii) a breakup-transfer mechanism and (iii) an evaporation-like process. We suggest that the breakup-transfer process is a quasi-free (d, t) single-neutron pickup reaction in which a proton from the ^3He projectile is a spectator. The relative importance of the different processes has been determined from coincidence experiments on natSi.

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